

# S-transform view of geomagnetically induced currents during geomagnetic superstorms

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[1] A novel time-frequency analysis method (S-transform) capable of handling noisy non-stationary signals is applied to study the properties of geomagnetically induced current (GIC) fluctuations in the Finnish natural gas pipeline. New local time- and storm phase-dependent S-transform spectral properties of auroral region GIC fluctuations during geomagnetic superstorms are reported. More specifically, the S-transform spectra have two distinct regions containing the most of the spectral power that persisted from storm to storm: main phase-related wide-band fluctuations driven possibly by a substorm-type ionospheric activity centered around the local midnight and recovery phase-related narrow-band fluctuations associated with Pc5 range geomagnetic pulsations in the local morning region. Based on this observed “stability”, a new S-transform-based statistical approach using, for example, an ensemble of different S-transform responses for known storms is proposed for GIC prediction. **Citation:** Pulkkinen, A., and R. Kataoka (2006), S-transform view of geomagnetically induced currents during geomagnetic superstorms, *Geophys. Res. Lett.*, **33**, L12108, doi:10.1029/2006GL025822.

## 1. Introduction

[2] Geomagnetically induced currents (GIC) flowing in long technological conductor networks on the ground are one of the manifestations of geomagnetic storms and can be thought as an end link of the chain of processes from the surface of the Sun to the surface of the Earth. GIC is not only an interesting geophysical phenomenon but it also has a space weather aspect; that is, it poses a potential threat to the normal operation of technological systems using long conductors [see, e.g., Boteler *et al.*, 1998].

[3] The fundamental challenge of the GIC research is to identify, understand and model different geophysical processes associated with large GIC events posing the greatest threat to the technological systems on the ground. The present understanding is that a number of different geophysical processes are capable of driving large GIC; sudden geomagnetic commencements, geomagnetic pulsations and auroral substorms in particular have been identified as important causes for large GIC [Boteler, 2001; Lam *et al.*, 2002; Kappenman, 2003; Pulkkinen *et al.*, 2003, 2005]. However, in principle, any rapid temporal change in the

solar wind-magnetosphere-ionosphere system can cause large GIC.

[4] Most of the earlier studies (e.g., those cited above) on the ionospheric and magnetospheric drivers of GIC have been more or less event-based and did not provide any direct means for generalizations. Rigorous statistical analyses of GIC and the time derivative of the horizontal ground magnetic field (denoted hereafter as  $dB/dt$ ), a quantity closely coupled to GIC via Faraday’s law of induction, have been carried out by Viljanen *et al.* [2001, 2006], Weigel *et al.* [2002]; Weigel and Baker [2003], Wintoft [2005], and Pulkkinen *et al.* [2006]. However, none of these studies focused on the geomagnetic superstorms which will be investigated in this work. Also, here the GIC fluctuations are characterized by a novel time-frequency analysis method called S-transform [Stockwell *et al.*, 1996], which is capable of handling noisy non-stationary signals.

## 2. Data and the Analysis Method

[5] The main data to be analyzed is composed of GIC measurements carried out (since November 1998) in the Finnish natural gas pipeline at Mäntsälä pipeline section [Pulkkinen *et al.*, 2001]. The coordinates of the measurements site are 57.8° MLAT, 113.8° MLON and the data are obtained with a 10-second temporal resolution. Although the location of the measurement site is in overall average sense rather in the subauroral than in the auroral region, due to the southward movement of the auroral oval during strong storms, we will refer the region as auroral. The local magnetic time at Mäntsälä is roughly UT plus three hours.

[6] Since the focus of the study is on extreme events, we will analyze data only from the ten most intense geomagnetic storms that occurred during the years 1999–2005. One-hour resolution *Dst*-index is used to measure the strength of the storm. Analyzed storms, all having the minimum *Dst*-index peak value less than −250 nT, are listed in Tables 1 and 2 where the storms are divided into two categories based on the time (the local time of the GIC measurement site used as a reference) of the occurrence of the *Dst*-index peak value.

[7] S-transform [Stockwell *et al.*, 1996] of a signal  $h(t)$  is defined as an extended form of the short-time Fourier transform

$$S(\tau, f) = \int_{-\infty}^{\infty} h(t)g(\tau - t, f)e^{-i2\pi ft} dt \quad (1)$$

with Gaussian window

$$g(\tau - t, f) = \frac{|f|}{\sqrt{2\pi}} e^{-\frac{f^2(\tau - t)^2}{2}} \quad (2)$$

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**Table 1.** List of Storms for Which the *Dst*-Index Minima Occurred at the Local Midnight Sector Between 19–01 UT

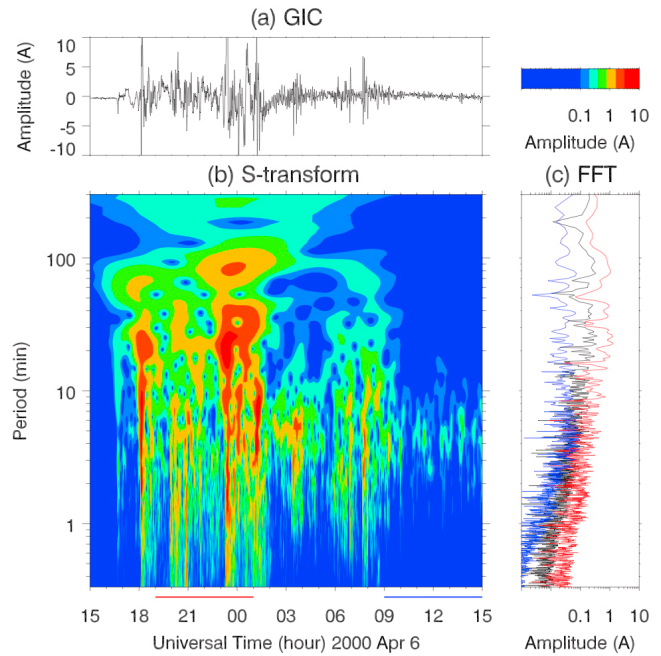
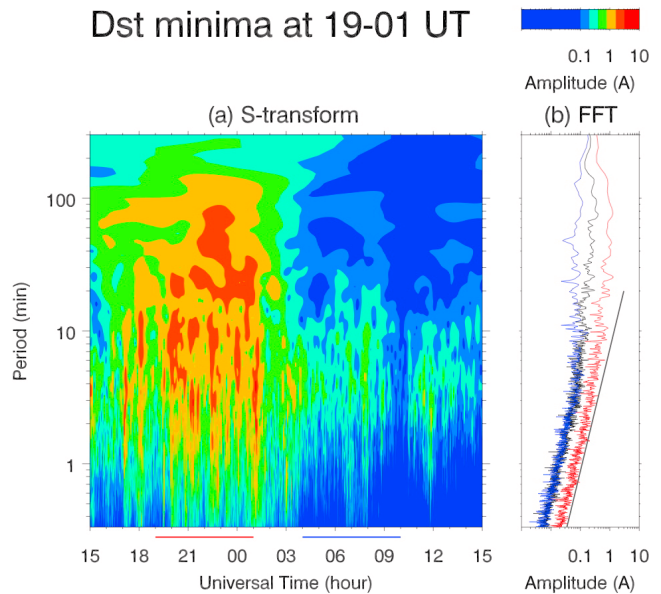
Year	Month	Day	Min( <i>Dst</i> )		max(abs(GIC)), A
			Hour, UT	Min( <i>Dst</i> ), nT	
2000	04	07	01	−288	23
2000	07	16	01	−301	30
2001	04	11	24	−271	22
2003	10	30	01	−363	57
2003	10	30	23	−401	49
2003	11	20	20	−472	24

where  $f$  is the frequency, and  $\tau$  is the center time of the Gaussian window. One of the fascinating properties of the S-transform is that the time averaging (i.e., integration over  $\tau$ ) of the S-spectrum defined by equation (1) yields the standard Fourier spectrum. It follows, that the S-transform is directly comparable to classic Fourier theories, which is not easily realized by other time-frequency analyses such as continuous wavelet transforms.

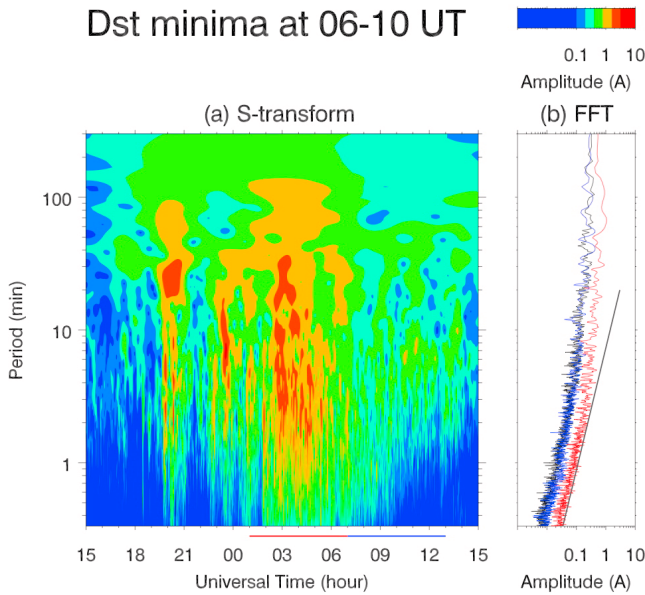
[8] The S-transform spectra of the recorded GIC are calculated using the time interval of 28 hours spanning the *Dst*-index minimum (see Tables 1 and 2). However, only spectra of 24 hour time intervals centered at 03 UT are shown; the 2 hour margins at the both sides are used to reduce the artificial edge effects. Further data processing steps were: 1) Hanning window was applied on the 5 per cent of the points at the edges to further reduce the edge effect, and 2) Hilbert transform was used to obtain analytic signal, localizing the spectra to positive frequencies. Finally, the amplitude  $|S(t, f)|$  was color coded to display the S-transform spectra.

### 3. S-Transform View of the GIC Fluctuations

[9] In Figure 1, GIC, the S-transform  $|S(t, f)|$  of GIC and the Fourier spectra (integrated S-transform) are shown for the April 6–7, 2000 geomagnetic storm period. The first obvious observation is that there is more or less continuous wide-band GIC activity roughly between 17–02 UT after which fluctuations undergo quite dramatic transition to a relatively narrow-band activity. The narrow-band fluctuations lie in the Pc5 geomagnetic pulsation range. Another important feature of the S-transform view is that there are breaks at the wide-band fluctuations. First break occurs at period of about 4 minutes up to which the fluctuations scale roughly as a power-law (this break is more pronounced in the average views shown in Figures 2 and 3). The second break occurs at period of about 150 minutes after which the power of the fluctuations starts to decrease. This behavior can be verified especially from the Fourier spectra of the wide-band regions shown red in Figures 1, 2 and 3. The

**Figure 1.** (a) GIC measured at the Finnish pipeline during the April 6–7, 2000 geomagnetic storm, (b) S-transform spectra of GIC, and (c) Fourier spectra obtained by integrating the S-transform spectra. Black curve, S-transform spectra integrated over the entire range. Red curve, S-transform spectra integrated over the range indicated by the red horizontal line. Blue curve, S-transform integrated over the range indicated by the blue horizontal line.**Figure 2.** (a) Mean S-transform spectra of GIC during geomagnetic storms given in Table 1 and (b) Fourier spectra obtained by integrating the mean S-transform spectra. Black curve, S-transform spectra integrated over the entire range. Red curve, S-transform spectra integrated over the range indicated by the red horizontal line. Blue curve, S-transform integrated over the range indicated by the blue horizontal line. The straight black line indicates the approximate range 0.5–4 minutes of the power-law scaling.**Table 2.** List of Storms for Which the *Dst*-Index Minima Occurred at the Local Morning Sector Between 06–10 UT

Year	Month	Day	Min( <i>Dst</i> )		max(abs(GIC)), A
			Hour, UT	Min( <i>Dst</i> ), nT	
2001	04	01	09	−387	16
2001	11	07	07	−292	32
2004	11	09	07	−373	35
2004	11	10	10	−289	43



**Figure 3.** Same as in Figure 3 but for geomagnetic storms given in Table 2.

most of the power of the wide-band fluctuations is confined within these breaks.

[10] One distinct feature of all S-transform figures shown in this paper is their “flame”-like (or spotty) appearance. This feature originates from the noise-like character of the GIC signal as can be seen by comparing Figure 1 to Figure 4 where we show S-transform spectra of a noise signal having autocorrelation time compatible with a break at the power spectrum at a period of about 4 minutes [for a relation between the power spectrum and the autocorrelation of a signal see, e.g., *Gardiner*, 2004]. The noise was created using formula [e.g., *Torrence and Compo*, 1998]

$$x_n = \alpha x_{n-1} + z_n \quad (3)$$

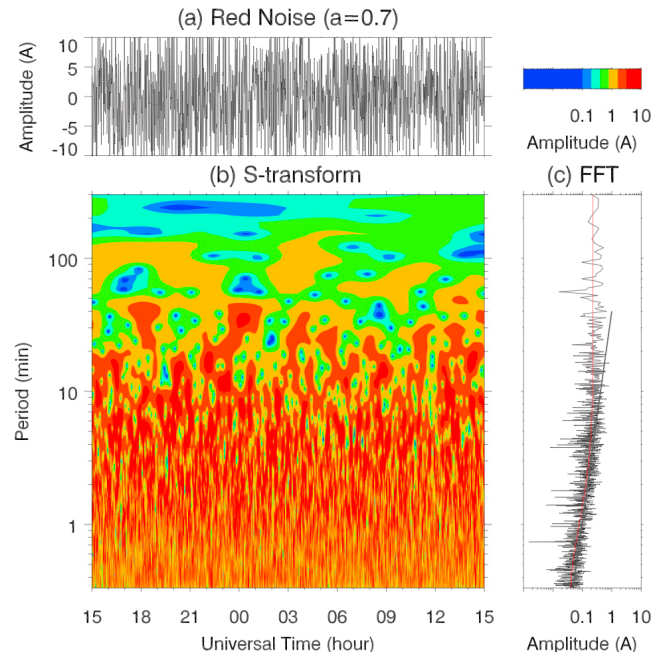
where  $z_n$  is Gaussian white noise and  $\alpha$  a constant determining the autocorrelation time of the noise. In fact, a study by *Pulkkinen et al.* [2006] revealed that the temporal behavior of auroral  $dB/dt$  (and thus also GIC) is very similar to that of white noise and that a possible deterministic component may be buried under these complex variations.

[11] Although not shown here, the geophysical origin of the spectral features of the GIC signal was verified by looking at the S-transform spectra of  $dB/dt$  recorded at the nearby Nurmijärvi Geophysical Observatory (located about 30 km south-west from the GIC measurement site). As expected (for detailed discussion about the relation between GIC and  $dB/dt$  see, e.g., *Viljanen et al.* [2001]), all the basic features were almost identical between the GIC and  $dB/dt$  spectra thus confirming that the detected S-transform characteristics (like the strong noise-like component) of GIC are not artificial.

[12] Moving then to a one step more general view of the GIC fluctuations, we divide the geomagnetic storms into two categories: to those during which the *Dst*-index minima occurred between 19–01 UT and to those during which the

*Dst*-index minima occurred between 06–10 UT. These two categories are listed in Tables 1 and 2 and the S-transforms for these storm periods are averaged separately. The aim of the separation is to investigate if there are any storm phase dependences on the GIC fluctuations. Such dependence is indeed detected from Figures 2 and 3 where the average S-transform spectra for the two storm categories are shown. The region of the wide-band fluctuation is clearly seen to move toward local morning hours for storms having the *Dst*-index minima at the local morning time (06–10 UT). However, other than the shift of the wide-band fluctuations region, the structure of the S-transform spectra look very similar: the wide-band fluctuations are confined approximately within periods 4–150 minutes and there occurs, although for post-midnight storms the change is not as dramatic, a transition from wide-band to narrow-band fluctuations.

[13] Importantly, a clearly identifiable similarity can be seen between the S-transform spectra for individual event in Figure 1 and the average views of Figures 2 and 3. As can be verified from Tables 1 and 2, all storms are roughly equal in terms of GIC amplitudes and thus the similarity is not caused by the dominance of a one single event; the similarity is due to the tendency of GIC to respond similarly to major geomagnetic storm driving. However, one should note that all of the analyzed storms have the time of the *Dst*-index minima within 19–10 UT. Thus, direct generalization to situations, for example, where the minima occurs around local post-noon time cannot be done. Also, it is clear that



**Figure 4.** (a) Noise with autocorrelation time of about 4 minutes generated using equation (3), (b) S-transform of the noise, and (c) Fourier spectra obtained by integrating the S-transform spectra. The straight black line indicates the approximate range 0.5–4 minutes of the power-law scaling. Compare to Figure 1. The red line shows the analytical spectrum calculated for the process described by equation (3).

more definite generalizations require much larger sample size than the one we were able to use here.

#### 4. Discussion

[14] From the general geophysical viewpoint the most important new finding of the study is that despite the large noise-component of the signal, we are able to identify distinct local time- and storm phase-dependent regions in the S-transform spectra of the GIC fluctuations that tend to persist for geomagnetic superstorms. The first is a storm main phase-related wide-band fluctuations region in the vicinity of the local midnight. The most of the power of these fluctuations is confined within the periods of about 4–150 minutes. The second is a storm recovery-related region located in the local morning region and has fluctuations centered around the Pc5 range. The amplitudes of the Pc5-related fluctuations are slightly smaller than those in the region with the wide-band fluctuations.

[15] The more definite identification of the physical mechanisms behind the detected GIC fluctuations naturally requires combined analysis of the ground- and the space-based data. Anyhow, based on the auroral location of the GIC measurement site and the centering roughly around the local midnight, it is relatively safe to suggest that the local midnight fluctuations are related to a substorm-type activity [e.g., Rostoker, 1996]. The fluctuations in the local morning region are clearly related to Pc5 range geomagnetic pulsations [e.g., Baker *et al.*, 2003]. This suggests that the substorm-type activity and the geomagnetic pulsations are the two most important causes for large GIC at the auroral region during major geomagnetic storms. This is in agreement with the event-based studies that were cited in the Introduction of the paper.

[16] The very complex temporal behavior of the auroral region GIC, demonstrated also in Figure 1a and the “flame”-like appearance of the S-transform spectra (cf. to completely unpredictable white noise in Figure 4), and corresponding ground  $dB/dt$  has been recognized to hinder an accurate deterministic prediction of GIC [Wintoft, 2005; Pulkkinen *et al.*, 2005; Pulkkinen *et al.*, 2006]. Here it was demonstrated that in contrast to this extreme variability of GIC, there are central characteristics in the S-transform spectra of GIC that are common for major geomagnetic storms. This observation suggest a statistical estimation of GIC levels based on the local time- and storm phase-dependent S-transform spectral amplitudes. In the simplest form this could mean that an ensemble of S-transform spectra are created using historical major storms and the ensemble is then used to pick the most probable S-transform response of GIC for the predicted storm characteristics expressed, for example, in terms of the UT of the *Dst*-index minimum.

[17] We note that there exists a clear connection between our results and the results by [Weigel *et al.*, 2002] who found that 30-minute average auroral  $dB/dt$  fluctuations are more predictable in the local post-midnight and the local morning regions (where the signal strength is the largest) than in other regions. Those predictable 30-minute averages

possibly relate to the wide-band fluctuations and the Pc5 pulsations detected here.

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